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Original Research

The Comparison of Plantar Pressure Distribution and Frequency Content of Selected Muscles Between Hydrodynamic and Typical Sport Shoe

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ABSTRACT

This study aimed to compare plantar pressure distribution and muscle frequency between hydrodynamic and typical sports shoes. Twelve healthy adult males participated in this experimental study. The hydrodynamic shoe features an outer sole with a pathway for fluid flow. The typical sports shoe with Ethylene-Vinyl Acetate soles was used for the comparison. Plantar pressure distribution was measured using the Pedar insole system, and the results were analyzed using Pedar-X software. Electrical muscle activity of the Gastrocnemius, Soleus, Palmaris longus, and tibialis anterior were measured using the Myon electromyography system at a 1000Hz sampling rate. Subjects were randomly assigned to wear either hydrodynamic or typical sports shoes and walked through the end of the pathway five times at a self-selected speed. The plantar area was divided into eight regions, and plantar pressure variables were calculated within these areas. The frequency variable includes mean and median frequency, as well as the 99.5th percentile frequency, representing 99.5% of the signal. Additionally, the bandwidth frequency was calculated. Paired t-test was used for statistical comparison ($p<0.05$). The results indicated considerable pressure reduction in the heel, forefoot, and toe ($P<0.05$). However, there is no difference in the time and frequency content of muscle activity between conditions. Based on the results, it seems that hydrodynamic shoes could have an important effect on the reduction of plantar pressure without any change in muscle activity during the gait.

Key Words: Plantar pressure distribution, EMG, frequency, hydrodynamic shoe

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INTRODUCTION

Gait is considered one of the most common functional activities due to its simplicity and safety, particularly among adults and the elderly. However, research has indicated that prolonged periods of walking may pose risks to the lower limb, particularly the plantar area of the foot. Muller et al., (1999) reported that pressure on the plantar area of the foot could lead to injury in three different aspects; applying large pressure, applying low pressure over a long period, and applying repetitive moderate pressure for a moderate time [1]. So, it seems that gait over a long period may cause different types of injuries for the plantar area or lower limb muscles, especially for patients with neuropathy such as diabetes [2]. Previous researchers reported that using therapeutic shoes can reduce plantar pressure in the sensitive area of the foot [2-4], and also reduce the risk of gait-related injuries. Previous research indicated that the use of special materials such as Ethylene-Vinyl Acetate (EVA) shoes, Rocker bottom shoes, and the silicon insole could effectively reduce the plantar pressure distribution [5-7]. Also, it has been proposed that the use of motion-control shoes could be very effective in lowering fatigue-related increases in mechanical loading following ground contact [8, 9]. In a previous study, it was revealed that costume shoes could significantly reduce planar pressure during walking compared to barefoot [10]. Insoles also have a considerable effect on the reduction of plantar pressure distribution and it was shown that therapeutic insoles could reduce pressure by an increase in contact area [11]. However, there is a hypothesis suggesting that the utilization of fluid for load absorption may lead to pressure reduction through mechanisms beyond simply increasing contact area. It is speculated that the pressure reduction achieved through this method could potentially be more effective.

It also could be noted that because of saving energy mechanisms during gait such as inverted pendulum [12, 13], the energy consumption during motion was low. Therefore, only a long-distance gait will be effective for burning calories. Previous researchers analyzed shoes with different sole materials during gait [13-16]. These researchers indicated that the use of compliant material increases lower limb muscle contractions [13-16]. However, some works believed that the utilization of some materials could lower muscle activity during gait [17, 18].

In this study, a novel shoe featuring hydrodynamic functionality was introduced, incorporating fluid to potentially absorb impact forces through plastic deformation during the stance phase following each step. Additionally, it was hypothesized that the viscosity of the fluid and its flow through the pathways could lead to changes in both the magnitude and frequency of muscle activity. Hence, the central question addressed in this research is whether a fluid with a specific viscosity, flowing within these pathways, effectively absorbs deformation energy and alters the frequency content of muscle activity during gait. Therefore, the objective of this study was to compare plantar pressure distribution and muscle frequency content between hydrodynamic shoes and typical sports shoes.

MATERIAL AND METHODS

Twelve healthy adult men were selected for this quasi-experimental work with a convenience sampling method. Subjects had no experience of muscle-skeletal injuries effective on gait pattern. The Mean (SD) of age, weight, and height of subjects were 24.9±3.8 years, 86±7.2 kg, and 178.7±6.4 cm, respectively. All subjects were informed about the purpose of the study. All of the experiments were performed in the laboratory of the Sport Sciences Research Institute of Iran.

The hydrodynamic shoe features an outer sole made of lightweight ethylene-vinyl acetate (EVA), complemented by an inner silicon capsule embedded within the EVA sole. Moreover, the silicon capsule incorporates specialized pathways configured to facilitate the flow of fluid within the shoe.

The fluid viscosity and pathway configuration were designed based on the mechanics of human gait, so moving the fluid into the pathway could absorb contact energy. During the pre-swing to the push-off phase of walking, the intrinsic and extrinsic muscles of the foot and ankle have to work harder to push fluid in the hind-foot area to effectively create propulsion force on the ground during push-off. The final design of the shoe sole includes an inner layer and an outer layer. The inner layer of the hydrodynamic shoe is a silicon firm of 3 mm thickness with 97.8 Gigapascal (GPa) strength for hydrostatic load, and the outer layer is made of Polyurethane foam (PU), which is the most common material used in the shoe sole. The final design of the shoe sole was created using Shoemaker software version 2016.

Electromyography (EMG) was measured using the Myon electromyography system. The EMG electrodes were placed on the gastrocnemius, soleus, palmaris longus, and tibialis anterior muscles with a 2 cm inter-electrode distance. Electrode placement was performed based on the SENIAM protocol and sampling rate was selected at 1000 Hz [19]. Pedar insole system (novel Gmbh, Germany) was used to measure vertical ground reaction force (VGRF) and plantar pressure distribution. To measure these variables, the Pedar insole was placed into the shoe. Then, subjects walked through the 10 m walkway at a self-selected speed. Five correct strides of each foot were recorded [20]. The first and last steps were removed to avoid the familiarity process and fatigue effect, respectively [20]. Then the average of peak and mean pressure and contact areas of three steps were calculated using Pedar-x software [21].

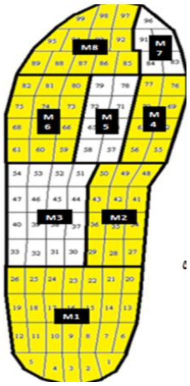

Figure 1. Eight masks of plantar area. M1=heel. M2= medial midfoot. M3=lateral midfoot. M4=first forefoot. M5= second forefoot. M6= lateral forefoot. M7= first toe. M8= other toes.

Pedar-X evaluation software was used to calculate the following variables in each mask: Peak pressure (Kpa), Mean pressure (Kpa), and contact area (cm^2). EMG data were analyzed using

MATLAB Software (R2016a). A bandpass filter (15-500 Hz) was used for data filtering. Onset and offset of muscle activation were calculated using the Mean±2Standard Deviation of baseline for a 50 ms time window. For the frequency analysis, Mean and Median frequency, Frequency with 99.5% power (f 99.5), and Frequency Bandwidth were calculated [22]. Mean and standard deviation were used for descriptive analysis. Moreover, a paired t-test was used for the detection of significant differences between hydrodynamic and sports shoes. All statistics were carried out using the SPSS 20.0 statistical software package with an overall significance level set at $p<0.05$.

RESULTS

The results of the Paired t-test in Tables 1 to 4 show that there are no significant differences between mean activity and frequency content between EVA and Hydrodynamic shoes in all of selected muscles ($P>0.05$) (Table 1-4).

Table 1. The mean, standard deviation, and the results of the Paired t-test of the normalized EMG and frequency data in Gastrocnemius

Variable	Shoe	Mean	SD	Min	Max	t value	p value
Mean Frequency (Hz)	SPORT SHOE	111.26	14.24	82.48	135.80	0.332	0.75
	Hydrodynamic shoe	109.99	14.21	80.46	133.08		
Median Frequency (Hz)	SPORT SHOE	82.35	14.35	51.30	109.54	0.25	0.8
	Hydrodynamic shoe	81.34	15.56	50.70	109.79		
F99.5 (Hz)	SPORT SHOE	253.27	203.48	43.90	748.70	0.99	0.32
	Hydrodynamic shoe	210.04	132.28	49.93	528.13		
Frequency Bandwidth (Hz)	SPORT SHOE	30.28	13.89	5.65	58.82	0.7	0.48
	Hydrodynamic shoe	27.94	13.68	5.13	76.07		

Table 2. The mean, standard deviation, and the results of the Paired t-test of the normalized EMG and frequency data in Soleus

Variable	Shoe	Mean	SD	Min	Max	t value	p value
Mean Frequency (Hz)	SPORT SHOE	107.47	11.54	87.63	122.98	0.59	0.55
	Hydrodynamic shoe	105.40	12.78	76.13	124.38		
Median Frequency (Hz)	SPORT SHOE	79.63	12.20	55.28	95.22	0.67	0.5
	Hydrodynamic shoe	77.24	12.60	48.79	94.97		
F99.5 (Hz)	SPORT SHOE	244.79	117.87	53.90	545.20	0.99	0.32
	Hydrodynamic shoe	215.59	117.38	46.14	548.77		
Frequency Bandwidth (Hz)	SPORT SHOE	33.59	15.42	2.44	62.62	0.76	0.45
	Hydrodynamic shoe	30.52	13.52	5.37	64.23		

Table 3. The mean, standard deviation, and the results of the Paired t-test of the normalized EMG and frequency data in Palmaris longus

Variable	Shoe	Mean	SD	Min	Max	p value	t value
Mean Frequency (Hz)	SPORT SHOE	115.41	12.29	90.10	130.01	0.18	0.85
	Hydrodynamic shoe	116.06	14.11	91.38	135.75		
Median Frequency (Hz)	SPORT SHOE	86.64	13.67	57.48	106.95	0.05	0.96
	Hydrodynamic shoe	86.85	16.02	53.98	107.57		
F99.5 (Hz)	SPORT SHOE	180.43	139.84	45.26	619.36	0.25	0.8
	Hydrodynamic shoe	173.73	95.28	45.26	405.78		
Frequency Bandwidth (Hz)	SPORT SHOE	27.34	11.74	7.26	62.57	0.07	0.94
	Hydrodynamic shoe	27.62	15.86	-9.70	54.40		

Table 4. The mean, standard deviation, and the results of the Paired t-test of the normalized EMG and frequency data in Tibialis Anterior

Variable	Shoe	Mean	SD	Min	Max	t value	p value
Mean Frequency (Hz)	SPORT SHOE	99.68	7.63	88.45	115.62	0.43	0.67
	Hydrodynamic shoe	100.74	9.51	89.15	121.39		
Median Frequency (Hz)	SPORT SHOE	72.15	8.13	58.97	92.55	0.26	0.79
	Hydrodynamic shoe	72.86	10.32	58.94	96.38		
F99.5 (Hz)	SPORT SHOE	184.50	92.07	49.61	345.90	0.51	0.61
	Hydrodynamic shoe	196.67	94.19	42.85	417.50		
Frequency Bandwidth (Hz)	SPORT SHOE	25.86	11.72	-3.17	48.46	0.26	0.79
	Hydrodynamic shoe	25.11	10.53	4.28	43.30		

The results of the paired-t test indicated that there are significant differences in forefoot plantar pressure and first toe between SPORT SHOE and Hydrodynamic shoe (P=0.001) and it seems that plantar pressure was significantly lower in these areas (Table 5). The study found that the contact area in the first metatarsal region of the hydrodynamic shoe was significantly lower compared to the sports shoe. (P<0.02) (Table 5).

Table 5. The mean, standard deviation, and the results of the Paired t-test of the Peak pressure, Mean Pressure, and Contact areas of the Hydrodynamic shoe and sport shoe

Variable	Contact Area (mm2)		Mean Pressure (kPa)		Peak pressure (kPa)	
Mask	H-shoe	SPORT SHOE	H-shoe	SPORT SHOE	H-shoe	SPORT SHOE
Mask 1	45 (0)	45 (0)	115.11* (13.5)	148.2* (24.2)	154* (10.7)	240* (17.36)
P-value	-		0.03		0.007	
Mask 2	15* (4.8)	22.2* (0.24)	41.6* (15.4)	34.33* (11.3)	103.33 (10.8)	94.66 (9.77)
P-value	0.02		0.04		-	
Mask 3	26.33 (0.48)	28 (0)	65.49 (17)	71.7 (15.9)	99.16 (9/73)	121.3 (19.51)
P-value	-		-		-	
Mask 4	14 (0)	14 (0)	109.2* (20.6)	180.8* (23.7)	123.33* (30.77)	328.33* (72.48)
P-value	-		0.005		0.001	
Mask 5	14 (0)	14 (0)	101.5* (14.2)	139.6* (16.6)	124* (30)	190.67* (29.54)
P-value	-		0.045		0.01	
Mask 6	19 (0)	19 (0.12)	100.4* (11.17)	140.33* (10.42)	133.5* (39)	235* (43.68)
P-value	-		0.03		0.002	
Mask 7	8.5 (0)	8.5 (0)	186.7* (18.8)	246.6* (26.9)	285* (35.9)	404* (46.73)
P-value	-		0.008		0.001	
Mask 8	20 (0)	20.1 (0.16)	77.83 (11.2)	75.55 (13.19)	148 (15.49)	130.3 (25.81)
P-value	-		-		-	

*Significant differences in 0.05 level

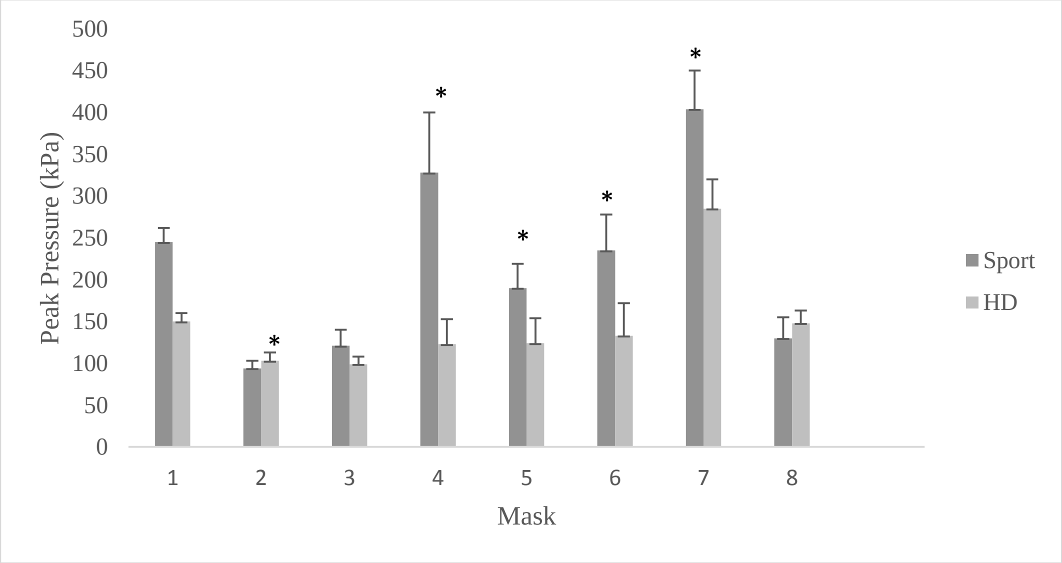

Figure 2. Peak pressure distribution in eight areas of the foot between Sport shoe and Hydrodynamic shoe (HD)

DISCUSSION

This study sought to assess the impact of hydrodynamic shoes on plantar pressure and muscle activity. The findings revealed that hydrodynamic shoes led to a significant reduction in plantar pressure distribution, particularly in the forefoot and first toe regions. However, the electromyography (EMG) results indicated no significant differences in the frequency content between hydrodynamic and sports shoes.

This result aligns with previous research findings that have demonstrated therapeutic footwear, incorporating special materials, to be effective in reducing plantar pressure distribution [10, 11]. While there is limited research comparing the frequency content of hydrodynamic and sports shoes, the findings regarding electromyography (EMG) in this study contradict previous research. Previous studies have suggested that the use of soft materials in shoe soles could lead to an increase in muscle activity during gait. However, the results of this study did not show significant differences in muscle activity frequency between hydrodynamic and sports shoes [10,14]. On the other hand, the results of this study are consistent with those of Peter et al (2020) stating that the activity of plantar flexors didn't change following the use of different shoe types [23].

Based on our results, the hydrodynamic mechanics had a different effect on gait mechanics than a softer shoe. Although the reduction of plantar pressure takes place in the hydrodynamic shoe, it seems that this reduction did not alter muscular frequency content. In the study of Altayyar et al (2016), it was revealed that costume shoes could significantly reduce planar pressure during walking compared to barefoot gait [10]. Insoles in previous papers also had a considerable effect on the reduction of plantar pressure distribution and it was shown that therapeutic insoles could reduce local pressure by an increase in contact area [11]. However, the reduction of plantar pressure in the forefoot and first toe was not because of an increase in the contact area. Only the one mask contact area was different between the two shoe conditions. The results of this study showed that the hydrodynamic shock absorbing mechanism could reduce peak and mean plantar pressure under the high-risk area of the foot (metatarsal and hallux) without any change in the contact area and muscle frequency content. The metatarsophalangeal joints [24], and metatarsal heads and hallux [25] are the high-risk foot areas for emerging foot ulcers based on works by previous researchers [26, 27], and this study shows that hydrodynamic shoes could reduce peak and mean plantar pressure in these areas.

In this study, four different muscles with distinct functions in the foot were utilized, under the assumption that any alterations in shoe function would be manifested through changes in the magnitude and frequency of muscle activity. However, the findings revealed that modifications in shoe sole mechanics did not lead to significant alterations in gait mechanics. The frequency analysis results indicated no significant differences in the frequency content between hydrodynamic and sports shoes. Muscle activity serves as an indicator of the number of motion units engaged in the task, with frequency analysis providing insight into the rate of this process. Therefore, these variables were expected to reflect any changes in motion mechanics associated with walking in different types of shoes. Based on Wurdeman et al (2011) frequency analysis should reflect any neuromuscular change following in change in variables like training [21]. In the study of Kin et al (2023), it was indicated that a change in muscle activity following a change in shoe type is correlated with cortical activity [28]. This finding shows that the reduction of plantar pressure following the use of a hydrodynamic shoe didn’t alter the activity pattern of muscle when using of standard shoe.

In this study, custom shoes featuring a hydrodynamic mechanism were introduced, designed to absorb mechanical energy during walking through the flow of fluid in a unique manner. These hydrodynamic shoes were equipped with a special fluid in their soles, possessing a viscosity ten times higher than the water-filled silicon layer embedded within the sole. The silicon capsule within the shoe incorporated specialized pathways to facilitate fluid flow during walking. As individuals walked in the hydrodynamic shoes, the impact force following each step was absorbed through complete plastic deformation induced by the flow of fluid. Consequently, muscular activity increased to overcome the viscosity of the fluid, resulting in a unique biomechanical response during walking [29, 30]. It seems that hydrodynamic shoes could keep muscle activation at a normal level during walking as the same mechanisms are used in walking with common materials. It is important to note that based on previous research, the hydrodynamic shoe could effectively reduce plantar pressure on the high-risk region of the foot [24]; therefore, it seems that increasing muscle activity and walking challenge could be completely safe and desirable.

It is important to note that since the primary focus of this research is on walking, the findings regarding the hydrodynamic effects of fluid may not directly apply to running situations.

CONCLUSION

The findings of this study demonstrate that custom hydrodynamic shoes offer a shock-absorbing advantage during gait. As a result, plantar pressure distribution was decreased, particularly under high-risk areas of the foot. The primary discovery of this research lies in the ability of the hydrodynamic shoe to attenuate pressure without inducing changes in normal muscle activity patterns. This suggests that the hydrodynamic properties of the shoe play a crucial role in mitigating plantar pressure without disrupting the natural muscle activation patterns during walking.

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Data Availability Statement: Data will not be available at request.

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مقایسه توزیع فشار کف پایی و فرکانس فعالیت عضلات بین کفش هیدرودینامیک و کفش ورزشی رایج

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چکیده:

هدف این مطالعه مقایسه توزیع فشار کف پایی و فرکانس فعالیت عضلانی بین کفش هیدرودینامیکی و کفش ورزشی رایج بود. ۱۲ آزمودنی سالم در این مطالعه بکار گرفته شدند. کفش مخصوص هیدرودینامیکی شامل لایه پلیمری بیرونی و لایه داخلی حاوی مسیرهایی برای عبور مایع می باشد و برای مقایسه از کفش استاندارد استفاده شد. توزیع فشار کف پایی با استفاده از سیستم پدار و فعالیت الکتریکی با استفاده از سیستم الکترمایوگرافی مایون اندازه گیری شد. فعالیت عضلات دوقلو، نعلی، درشت نی قدامی و نازک نی طویل با فرکانس ۱۰۰۰ هرتز در این مطالعه مورد اندازه گیری قرار گرفت. ناحیه کف پا برای بررسی توزیع فشار کف پایی به هشت بخش تقسیم شد. پس از تعیین آغاز و پایان فعالیت عضله، متغیرهای فرکانس میانه و میانگین، فرکانس با توان ۹۹٫۵ درصد و پهنای باند فرکانس به عنوان متغیرهای فرکانسی مورد محاسبه قرار گرفتند. نتایج این مطالعه حاکی از این مطلب بود که توزیع فشار کف پایی به دنبال استفاده از کفش هیدرودینامیک به طور قابل توجهی کاهش پیدا می کند ولی کاهشی در فرکانس فعالیت الکتریکی عضلانی مشاهده نشد. براساس یافته های این مطالعه استفاده از مایع در کفش می تواند به طور قابل توجهی توزیع فشار کف پایی را کاهش دهد بدون تغییر در الگوی بکارگیری عضلات و می تواند برای افراد حساس به توزیع فشار کف پایی نظیر افراد دیابتی مورد استفاده قرار گیرد.

واژگان کلیدی: توزیع فشار کف پایی، EMG، فرکانس، کفش هیدرودینامیکی